SCOPE OF WORK

Juvenile Salmon Passage through Culverts
Research on the Upstream Movement of Juvenile Salmon at the Culvert Test Bed at the Skookumchuck Rearing Facility

Task XX: Experiments on Culvert Retrofit Designs: Standard Baffles

Period of Performance: July-December 2005

INTRODUCTION & BACKGROUND

Washington State Department of Transportation (WSDOT), in cooperation with partner state and federal agencies, as well as private partners, is currently leading a unique pooled-funding program to study juvenile salmonid passage through road culverts and evaluate designs of retrofitted culverts to improve the success of upstream passage by juvenile salmonids. A majority of this research is being carried out at the Culvert Test Bed (CTB) facility at the Washington Department of Fish and Wildlife (WDFW) Skookumchuck Rearing Facility near Tenino, Washington. From 2003 to 2005, Battelle Pacific Northwest Division (PNWD) conducted hydraulic measurements and fish-behavioral research in a series of studies leading to evaluation protocols to be applied in further testing at the CTB during and beyond 2005.

Impassable road culverts located on federal, state, and private lands currently block thousands of miles of suitable juvenile rearing habitat. Therefore, optimal upstream passage conditions in culverts for juvenile salmon must be determined. One of the key areas of interest involves determining appropriate hydraulic and fish passage designs for retrofitted culverts. A retrofitted culvert is one in which the bed characteristics of an existing culvert are modified or engineered to improve fish passage. Considerable research on adult salmonid passage through retrofit culverts has been accomplished, but the optimal retrofit conditions for culvert passage by juvenile salmonids are not well understood.

To successfully negotiate a culvert, a fish must be able to enter the culvert, traverse the length of the barrel, exit the culvert, and proceed to an upstream resting area. Based on a review of current scientific literature, little is known about the capability of juvenile salmonids to access upstream habitat by overcoming barriers. The WDFW Fish Passage Design at Road Crossings Manual (WDFW 2003) currently has a design standard for baffles that was developed to provide adult salmon passage (Figure 1). Retrofit culverts that were designed by this method provide good passage for adult fish but passage success for juvenile fish is unknown. It is thought, that at low flow when the baffles are operating as weirs, if the drops (i.e., distance from water surface above the baffle to that below the baffle) are relatively small and the downstream pool volume is adequate, these retrofit culverts are passable to juvenile fish. Verification of this hypothesis is desirable.

This document describes the scope of work entailed in evaluating the passage of juvenile coho salmon through culvert systems, beginning with a culvert system configured with the WDFW standard baffles commonly used to enhance adult passage (Figure 1). This document provides a step-wise process and a statistical design framework for examination of a series of baffle configurations under a variety of culvert slopes and water flows.

PROGRAM GOAL & TASK OBJECTIVES

The overall goal of the CTB program is to identify culvert configurations and the associated hydraulic conditions that facilitate successful upstream passage of juvenile salmonids. The work described here will use the CTB and the 6-foot round corrugated steel culvert currently mounted in the CTB. The objectives of this task in the culvert retrofit testing phase of the CTB program are as follows:

- Determine the passage success of juvenile salmon swimming through a series of configurations of WDFW standard baffles under different culvert slopes and water flows.

- Relate fish passage success to culvert slope, water flow, water velocity, turbulence intensity, water depth, and Energy Dissipation Factor (EDF) for the installed retrofit design.

- Make recommendations for future culvert retrofit designs based on CTB test results.

The primary question in the first evaluation phase is what passage success is achieved for juvenile salmon with the WDFW standard baffle over a set of slopes and flows. Secondary questions are what changes in spacing, baffle height, or baffle angle enhance juvenile passage success.

RETROFIT EVALUATION TASK AND SUBTASKS

Initially, the 2005 CTB retrofit evaluation task will focus on fish passage testing and behavioral observations, as well as characterization of hydraulic conditions within the CTB with standard WDFW baffles installed. This first phase of the overall retrofit evaluation will consist of the following three subtasks:

1. *Mobilization of the CTB for Retrofit Evaluation.* This subtask mobilizes the CTB for the retrofit evaluations and establishes protocols and proficiency for changing baffles within the CTB.

2. *Evaluation of WDFW Standard Baffles for Passage by Juvenile Coho Salmon*. This subtask uses a combination of staircase trials and paired comparisons to evaluate passage success of juvenile coho salmon in a 6-foot round culvert with WDFW standard baffles installed. The staircase approach will be used to narrow the range of conditions (flow, slope, etc.) to a focused set to be used in the pair-wise comparisons. First to be conducted under the focused set of conditions are behavioral observations of fish during passage. Results of the behavioral

observations are used to select the conditions for the hydraulic measurements to be made primarily with the acoustic doppler velocimeter (ADV). A step-wise process that is described in more detail below (Figures 2 and 3) is anticipated and will use the results of one test series in deciding among the alternatives to evaluate next.

3. *Data Analysis and Technical Reporting*. This subtask will analyze the data collected and provide draft and final reports on the results.

Subtask 1: Mobilization of the CTB for Retrofit Evaluation

This subtask mobilizes the CTB for evaluation juvenile salmonid passage through a culvert system configured with WDFW standard baffles. The steps in the mobilization of the CTB include the following:

1. Purchase four (4) additional video cameras and lighting equipment to support retrofit testing and fish-passage behavioral observations at baffles within the CTB.

2. Install cameras, video recording gear, and ADV to support testing. With both the current and proposed video recording equipment, up to 8 cameras could be used to cover all baffle and other relevant positions within the CTB. The additional cameras and lights purchased as part of this task will allow for observation and recording of fish behavior at each individual baffle. In addition, it will enable hydraulic engineers to fully document flow conditions within the CTB and to focus on detailed flow-turbulence issues (e.g. streaming vs. plunging flow) at individual baffles.

3. Ensure all CTB and measurement systems are operational and properly functioning.

4. Develop protocols for installing, adjusting, and removing baffles in the CTB. WDFW will design, fabricate, and oversee initial installation of baffles in the CTB. WDFW personnel will train PNNL field personnel in proper baffle installation procedures. This task covers only the initial baffle installation and training session. The baffles will need to be removed and installed several times during the retrofit testing program. These subsequent baffle change operations will be included in later tasks.

5. Develop revised protocols for water flow management at the CTB. Due to modifications of the hatchery water system that serves the CTB, a revised flow-control procedure is required. This sub-task will require coordination with WDFW staff and CTB personnel, as well as a dedicated training session for fish-testing staff and hydraulic-measurement technicians.

Subtask 2: Evaluation of WDFW Standard Baffles for Passage by Juvenile Coho

Salmon

This subtask provides observations of fish behavior and measurements of hydraulic parameters to support the evaluation of juvenile salmonid passage through a culvert configured with WDFW standard baffles. The observations and measurements are intended to address a primary question and a set of secondary questions, as follows:

- Primary: What is the passage success of juvenile coho salmon in a culvert system configured with the WDFW standard baffles commonly installed to enhance adult salmon passage?

- Secondary: For a particular baffle configuration, what changes in the spacing between baffles increase or decrease juvenile salmonid passage success? Similarly, what changes in baffle height or in the angle at which the baffles are slanted enhance juvenile salmonid passage success?

Test Conditions

The CTB is described in the protocols report (Pearson et al. 2005) and will be used in all the evaluation trials described here. Pearson et al. (2005) also provides the details on the procedures for fish handling, conduct of trials, hydraulic measurements and calculations, and the basic conditions for testing. The test conditions are summarized as follows:

<u>Culvert and Flow</u>

Type: Round corrugated steel culvert (40-foot long, 6-foot diameter, 3-inch by 1-inch corrugations). This culvert is currently mounted in the CTB.

Slope: An experimental variable; Initially at 1.1% slope

Water Flows: An experimental variable

Baffle Design: WDFW standard baffles (Figure 1)

Baffle Heights: 15" to 12", 12" to 9", 9" to 6" (Figure 1)

Baffle Spacing: Initially set at 5', 20', and 35' upstream from the culvert outlet; to be modified based on slope (Figure 1)

Backwatering: Backwater to the plunge over the most downstream baffle

Pool depth: Adjust false floor in the tailwater tank to achieve 9" water depth (distance from water surface of pool to false floor).

Plunging and Streaming: Record condition during each trial. Plunging conditions are expected to occur at low slopes and streaming conditions, at high slopes and flows.

Trials

Time of day: All trials at night

Duration: 3 hours

Test Fish: Juvenile coho salmon from Skookumchuck Hatchery

Fish Size: Juveniles, Size will be that available at time of testing

Fish Handling: As in protocols report.

Fish Density: 2 fish per cubic foot of water volume

Fish Counting: Two observers independently count the fish from the headwater tank, the culvert barrel, and the tailwater tank.

Fish Measurements: Measure fork length of 20 fish from each trial after retrieval at end of trial.

Fish Behavior: Monitor video camera outputs; record behavior every ten minutes and at the time of an event.

Control Trials: Interwoven. See text below under section on Statistical Study Design.

Metrics for Passage Success: See text in section on Data Analysis (Subtask 3).

Hydraulic Measurements

Temperature: Record the air and water temperature for each trial

Water depth: Record readings from staff gages in headwater and tailwater tanks. Record readings in manometer tubes for each trial. Record the levels in the manometer tubes once each day when culvert is dewatered.

Turbidity: Record depth of visibility in headwater tank with staff gage or secci disc.

Water Flow: Record readings from in-line flow meter.

Water Velocity: Use Acoustic Doppler Velocimeter (ADV) for fine-scale measurement of water velocity and turbulence intensity.

Statistical Study Design

The basic unit of testing in the design of retrofit study is a set of trials at a given slope that provides measurements of passage success over a series of flows for each of two baffle configurations. Figure 2 provides a flow chart depicting the potential comparisons and the options to pursue given a certain outcome. For example, the first unit of testing will compare passage success rates over a series of flows for a bare culvert at 1.1% slope with passage success rates for a culvert configured with baffles of 9" height on the left slanting to 6" on the right (looking upstream). Each night both of the two configurations will be tested with the order of testing drawn at random. This approach takes advantage of the observation from previous testing (Pearson et al. 2005) that passage success rates varied more between nights than within nights. The number of flows to be tested will be 4 to 5 with 2 replicate trials per flow. Range-finding trials will be done initially to determine the approximate range over which passage occurs and to confirm that backwatering and pool depth have been adjusted appropriately. The flows to be tested are then selected based on the results of the range-finding trials. The output of each basic unit is a plot of passage success rate against water flow showing two curves, one for each configuration. The resulting plot will be used to evaluate whether one configuration has a pattern of passage success that is significantly enhanced compared to the other. The metrics for passage success and their alternative analyses are discussed in a separate section below.

The outcome of the pair-wise comparison supports decisions concerning which one of two options is to be pursued in the subsequent unit of testing. For example, if the 9"/6" baffle has a pattern of enhanced passage success, than the next comparison would be the 12"/9" baffles versus the 9"/6" baffles at 1.1% slope. If the 9"/6" baffles prove not to have a pattern of enhanced passage success compared to the bare (unbaffled) culvert, then the baffle would be modified and retested. As the testing moves to greater slopes, the baffle heights increase. At the end of the series of testing units depicted in Figure 2, the range of flows and slopes over which the baffle configurations support passage success will become evident. At that point, the questions to be addressed become directed toward how to modify the baffles to further enhance juvenile passage (Goal 2 in Figure 3).

In addition to measuring passage success, observations of fish at each baffle will be made and examined to determine the interaction between the physical structure of the baffled culvert, the hydraulic patterns, and the behavioral responses. The passage success measurements and the behavioral observations will be used to set priorities for the fine-scale measurements of water velocity and turbulence intensity. Hydraulic measurements will only be taken at selected combinations of slope and flow for the retrofit-CTB and at specific points within the culvert system. The intent is to use the observations of fish behavior as a guide to where to measure the hydraulic conditions.

It is critical to recognize the three distinct flow conditions possible at the baffles (i.e., plunging, transition or streaming), and it is desirable to conduct testing under plunging and streaming flow conditions, as well as within the transitional zone between these characteristic flows. The retrofit evaluation may be complicated by the fact that there is likely no clear threshold of flow transition in a baffled culvert. In such a case, there may be a need to consider separate assessments of streaming flows and plunging flows. Such a separation may occur in the overall testing if plunging conditions dominates at low slopes and streaming conditions at high slopes and flows.

Control Trials

The protocols report (Pearson et al. 2005) noted that fish behavior can vary with season and that passage success was related to fish size and other seasonal factors. To account for such changes during the course of the retrofit evaluations, control trials will be interwoven with the evaluation trials. We anticipate that each unit testing will be accomplished in about 10 working days. We propose that a control sequence be conducted each month. If there is more than a month between testing units, then we propose a control sequence at the beginning of resumed testing and then at one month or the end of testing whatever comes first. A control sequence will consist of at least two replicate trials with a bare culvert at 1.1% slope and a flow of 1.0 or 1.5 cfs. The first pair-wise comparison (Figure 2) will provide testing over a variety of flows and the results can be used to make fine adjustments to the control sequence procedures.

CTB Slope Change

This subtask will likely include at least one CTB slope change operation, but could include up to three slope changes. Because the culvert slope will likely be changed several times during retrofit-testing, protocols for changing the slope of the CTB will be developed and refined.

On-going Consultation

As the work progresses, a technical work-group consisting of Battelle, WSDOT, WDFW, and other participating partners will need to make decisions concerning the test sequence and specifically the baffle configurations and slope and flow conditions to be next tested. The flow charts in Figures 2 and 3 depict the decision forks potentially appearing as the work progresses. For this step-wise adaptive management approach to be effective, it will be critical to review data as it is collected and conference frequently with WDFW and WSDOT staff to assess the next direction to be taken.

Subtask 3: Data Analysis and Technical Reporting

Analysis of Passage Success and Behavioral Observations

Each trial will yield counts of fish found at the end of the trial in the headwater tank, the culvert barrel, and the tailwater tank. The basic metric for passage success from a trial is based on the fish in the headwater tank at the end of the trial. This basic metric is calculated by dividing the number of fish in the headwater tank at the end of the trial by the number of fish released into the tailwater at the beginning of the trial. A similar metric can be calculated for the fish in the culvert barrel at the end of the trial.

The behavioral observations and analyses of the video records is anticipated to yield data on the number of attempts made to pass a baffle and the amount of time spent resting behind a baffle. Other behavioral responses may be quantifiable as well.

Metrics for Passage Success

Each unit of testing will yield a plot of passage success rate versus water flow for each of two baffle configurations tested. Statistical analyses will be applied to assess whether one configuration shows a pattern of passage success that is significantly more enhanced than the other. Also, a metric or index to assess the overall success of a configuration is needed.

In the analyses, three alternative approaches to an overall success index will be examined. These alternatives include the following:

- **Basic integrated index**. In the first and most basic approach, the area under the curve for each configuration in a basic unit of testing is integrated and then the areas are compared. This first approach assesses the overall success of each configuration against other configurations.

- **Integrated index weighted by probability of flow encounter.** In the second approach, the area under the curve is divided into segments by flow, then each segment is multiplied by the probability of encountering that flow, and finally the products are summed. This second approach weights the passage success rates over a series of flow segments by the probabilities that the juvenile fish would encounter those flows in a real-world situation. The encounter probabilities will be derived from a composite hydrograph for a set of Washington State streams in which 6-foot culverts have been placed. This second approach assesses the overall success of a configuration against a flow regime likely to be encountered in the field.

- **Integrated index with comparison to peak passage success rate**. In the third approach, the area under the curve is segmented by flow and analyzed to derive two index values. This second approach assesses the overall success of a configuration against a flow regime likely to be encountered in the field. The first index value is the flow segment within which the highest or peak passage success rate was observed. The second index value is the flow segment within which the passage success rate has decreased with increasing flow to some criterion level of the peak passage success rate. This criterion level could be set at 25%, 10%, or 5% of the peak success rate. This third approach assesses the overall success of a configuration by indexing the flow at which passage success falls below a criterion level.

In the testing sequence, the baffle configurations are evaluated in a series of pair-wise comparisons. For the overall evaluation sequence, the above indices can be used to rank the configurations on at least an ordinal scale. The use of ratios to provide an overall ranking will also be examined. The results of this analysis will be an assessment of the passage success of juvenile salmon swimming through a series of configurations of WDFW standard baffles under different culvert slopes and water flows.

Hydraulic Measurements and Calculations

The hydraulic data will be analyzed to provide information on water velocity, turbulence intensity, and other hydraulic parameters. Calculations of derived hydraulic parameters will follow procedures described in Pearson et al. (2005).

Maintenance issues with culvert-baffles are extremely important. These issues include conditions that can lead to sediment deposition within a culvert. The Battelle hydraulics group will examine the velocity-turbulence data collected in relation to sediment movement criteria. WDFW currently has a minimum energy dissipation factor (EDF) guideline to make sure sufficient turbulence exists to flush sediments through a culvert. The Battelle hydraulics group will use the hydraulic data and literature on sediment transport to estimate the range of sediment sizes that could move for a given culvert configuration and flows.

Relationships between Behavioral Responses and Hydraulic Conditions

The primary evaluation of culvert performance will be based on the relationship between passage success rate and water flow. Examination of the relationship between passage success and water velocity, turbulence intensity, water depth, and EDF will also be conducted. Additional examinations of relationships between passage success rate and other hydraulic parameters will be undertaken in selected cases. Such cases will be selected based on whether the behavioral observations suggest an interaction between behavioral response and hydraulic features.

Recommendations for Culvert Retrofit Baffle Design and Configuration

The information derived from analysis of the overall evaluation results will be used to assess the primary and secondary questions described in the objectives section above. Assessments of the relative advantages and disadvantages of the configurations tested will be based on the test results.

PERSONNEL

CTB team members will be drawn from within the resources available to Battelle. Dr. Walter Pearson will be the Battelle program manager for the project and Dr. Christopher May will be the Battelle deputy program manger. Dr. Marshall Richmond and his staff will lead the hydraulic measurement tasks. Ms. Susan Sargeant, Ms. Kathryn Sobocinski, and Mr. Robert Mueller will be field team leaders for biological testing. Battelle staff, under the direction of Mr. Gary Dennis will provide logistical support, including changing CTB slopes as required during testing. Dr. John Skalski (UW) will provide statistical design and analysis support.

DELIVERABLES AND SCHEDULE MILESTONES

Periodic-interim reporting of activities at the CTB will be accomplished by electronic mail. The deliverables of this project are the Draft and Final Reports.

Task 1 Mobilization	By August 10
Task 2 Evaluations of WDFW Baffles	By September 20
Task 3 Data Analysis	By October 31
Task 4 Final Report	By December 10

REFERENCES

Pearson, W., M. Richmond, G. Johnson, S. Sargeant, R. Mueller, V. Cullinan, Z. Deng, B. Dibrani, G. Guensch, C. May, L. O'Rourke, K. Sobocinski, and H. Tritico. 2005. *Protocols for Evaluation of Upstream Passage of Juvenile Salmonids in an Experimental Culvert Test Bed.* PNWD-3525. Final reported prepared by the Battelle Pacific Northwest Division for the Washington Department of Transportation under On-Call Agreement Y-9031, Task AA.

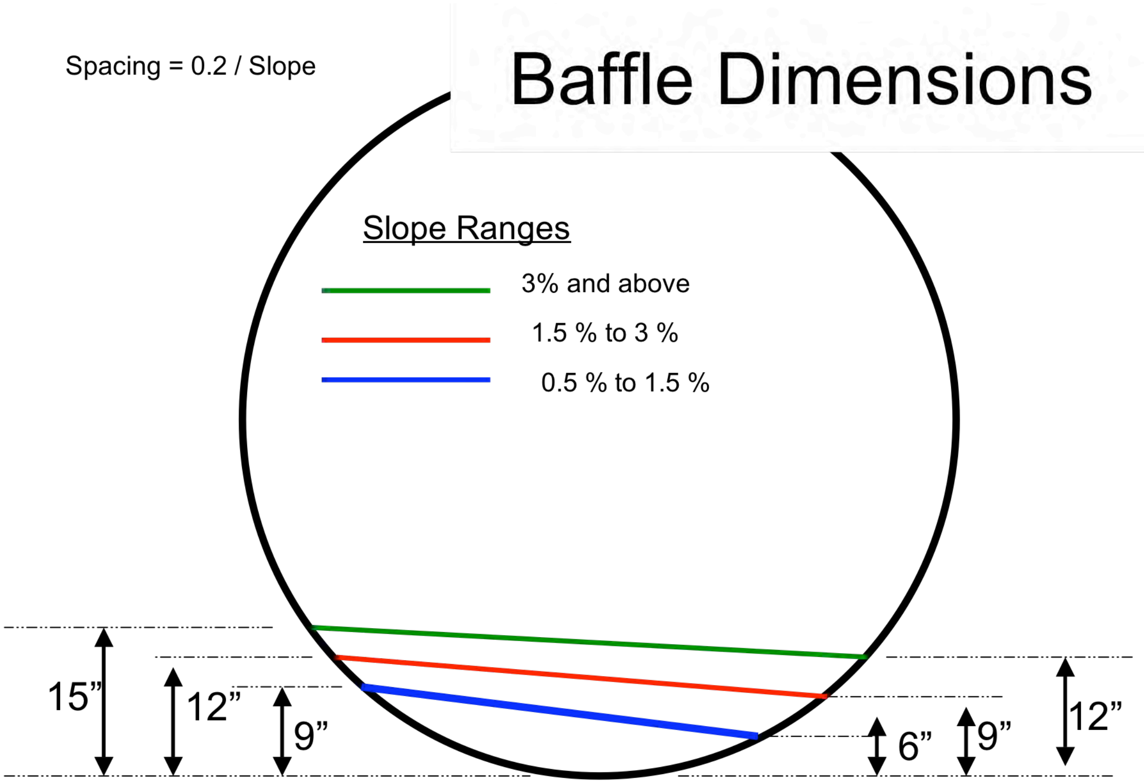

Figure 1. WDFW Standard Culvert Baffle Design.

Note: The baffle heights shown could be adjusted so the baffle slope is the same on all. Also, the 0.2 feet is for guidance, actual drop per baffle may vary depending on the low flow condition and slope, pool depth, etc.

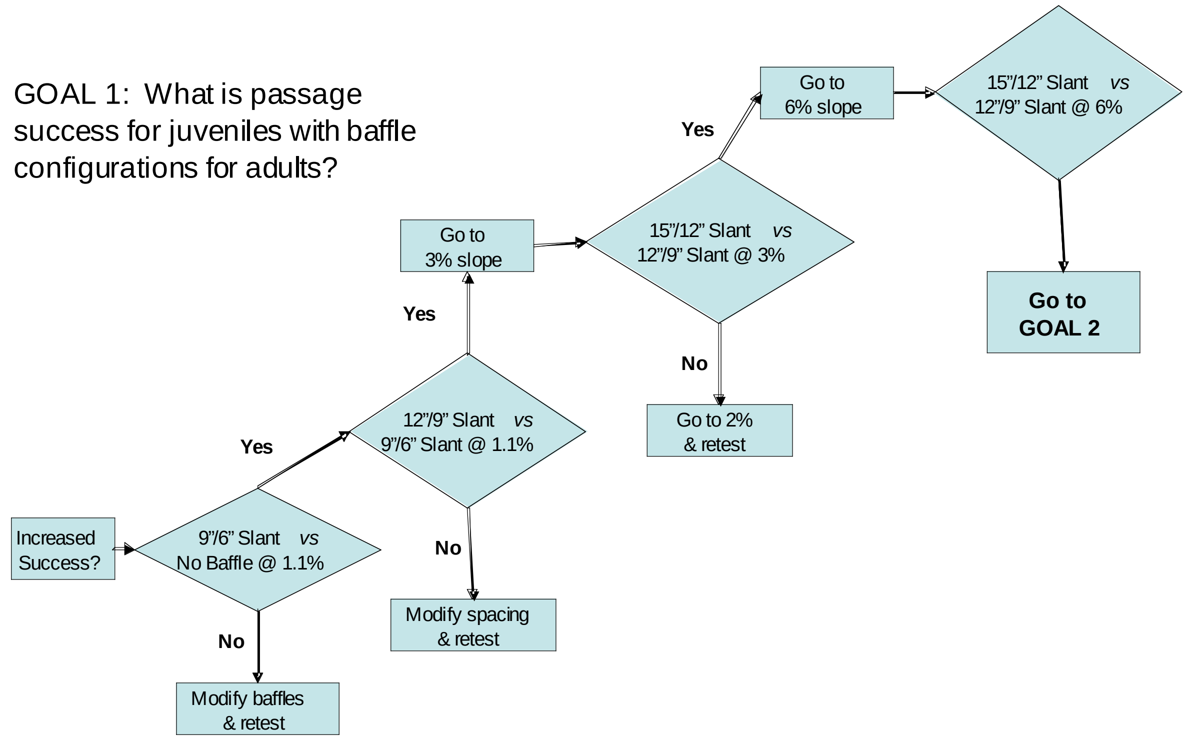

Figure 2. Flow Chart for The Assessment of Passage Success of Juvenile Coho Salmon in Culvert Test Bed with WDFW Standard Baffle Configurations for Adult Salmon.

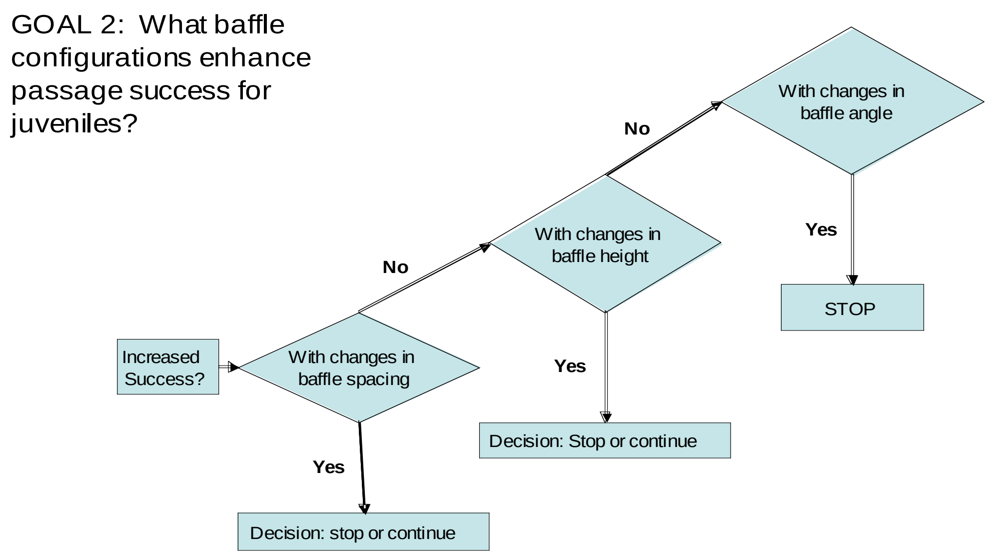

Figure 3. Flow Chart for Assessment of Modifications to WDFW Standard Baffle Configurations for Adult Salmon to Enhance Passage Success of Juvenile Salmon.